Lightning Induced Surges on an Unenergized Test Overhead Telecommunication Subscriber Line

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Abstract

Voltages induced on a test unenergized 1.8 km straight overhead telecommunication subscriber line by nearby lightning return stroke to ground is presented by solving transmission line coupling equations using time domain approach in combination with the numerical calculation of horizontal and vertical electric fields from return stroke current as inducing source.

Both horizontal and vertical electric fields have significant effect on induced voltages. The effect of the line length and line height on induced voltages is illustrated in this paper. A comparison between numerically calculated data and experimentally recorded data is also made in this paper. The ground conductivity is considered infinite and a triangular current pulse moving from ground to cloud through a 4 km upright vertical channel is taken as channel current. It is found that the calculated results are in reasonably good agreement with experimental results.

I. Introduction

Lightning is essentially a gigantic electrical spark that results from billions of volts of natural static electricity. During gigantic electrical spark it illuminates the surrounding media with a strong electromagnetic field that causes induced overvoltages and overcurrents on telecommunication subscriber and power lines. Induced overvoltages cause a devastating effect on solid state circuitry of modern electronic systems of telecommunication and power sectors and result in data corruption, system disruptions, component degradation, physical damages, and unnecessary down-time.

Numerous research have been conducted to investigate lightning induced behaviour on overhead power and telecommunication lines [1-6]. However, there has not been a comparison between numerical and experimental results. The content of this paper includes the numerical results showing the effect of line height and line length on induced voltages. The unique contribution of vertical and horizontal electric fields on induced voltages is also the scope of this paper. We have presented numerical results of induced voltages on a lossless 1.8 km straight overhead telecommunication subscriber line with diameter 1.27 mm placed at 5 m above perfectly conducting ground plane. Experimental data are recorded from an unenergized test line as mentioned above. The co-ordinate of strike points are collected from Tenaga National Research and Development (TNRD) Inc.. The coupling model proposed by Agrawal et al. [1] is used to calculate induced voltages in conjunction with the calculation of horizontal and vertical electrical fields. Finite difference technique is employed to solve the differential coupling equations. The numerical results calculated for side and front return strokes are compared with recorded data by using the co-ordinates supplied by TNRD.

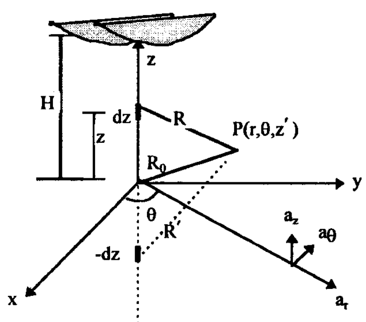

Fig. 1 Geometry of a model nearby lightning used in the vertical and horizontal electric fields computations at a point above the ground.

II. Theory

The geometry to explain a model lightning phenomenon is shown in fig. 1. Electric field radiated from lightning channel has two components, horizontal and vertical, which are both responsible for causing induced voltages in an overhead line. The vertical section

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of the overhead line is affected by the vertical component of electric field and the horizontal section by the horizontal electric field during induced voltages. The equations for electric fields due to the effect of the dipole dz at point P(r,ϕ,z′) in fig. 1 is expressed as follows [7,8] :

$$d\overline{E}_z = \frac{dz}{4\pi\varepsilon_0} \times \left[\frac{2(z-z')^2 - r^2}{R^5}\int_0^t i(z',t-R/c)dt + \frac{2(z-z')^2 - r^2}{cR^4} i(z',t-R/c) - \frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}\right]\overline{a}_z \quad (1)$$

$$d\overline{E}_r = \frac{dz}{4\pi\varepsilon_0} \times \left[\frac{3r(z-z')}{R^5}\int_0^t i(z',t-R/c)dt + \frac{3r(z-z')}{cR^4} i(z',t-R/c) + \frac{r(z-z')}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}\right]\overline{a}_r \quad (2)$$

where, $\overline{E}_r$ and $\overline{E}_z$ represent horizontal and vertical electric field intensity respectively, c is the velocity of light, μ_0 and ε_0 are the permeability and permitivity of free space, respectively. R, z, r, and z′ are defined in fig. 1. Both Equations (1) and (2) contain three terms; electrostatic, induction, and radiation terms. The first one dominates at small distances, the last one dominates at far distances and the middle one behaves intermediate between electrostatic and induction terms. The effect of infinite ground conductivity of the ground is included by considering an image dipole beneath the ground plane at the same distance as with the dipole dz above the ground when the ground plane is absent. The electric field produced due to the image dipole at point P(r,ϕ,z′) is determined from equation (1) and (2) by substituting R′ for R and -z for z. The total field at point P(r,ϕ,z′) due to the dipole at point (0,0,z) is the sum of dipole and image dipole field. Electric field for the whole channel is determined from the integration of dipole field through out the channel.

To calculate induced voltages on overhead telecommunication subscriber line, the time domain Agrawal et al.[1] model is adopted which is as follows:

$$\frac{\partial}{\partial y}V^s(y,t) + L\frac{\partial}{\partial t}I(y,t) = E_y(y,h,t) \quad (3)$$

$$\frac{\partial I(y,t)}{\partial y} + C\frac{\partial}{\partial t}V^s(y,t) = 0 \quad (4)$$

where $I(y,t)$ is the line current, $V^s(y,t)$ the scattered voltage, $E_y(y,h,t)$ the horizontal component of electric field at height h in absence of the subscriber line, directed positive from left to right along the subscriber line. L and C are the per unit length inductance and capacitance of subscriber line respectively.

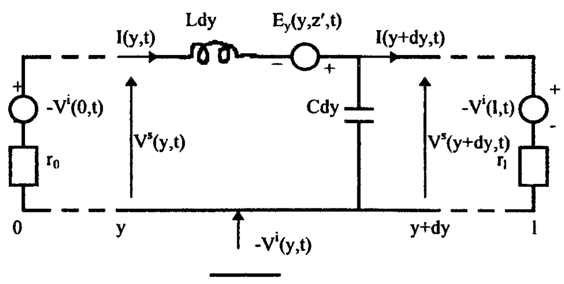

Fig. 2. Differential equivalent coupling circuit for a single-wire lossless overhead telecommunication subscriber line

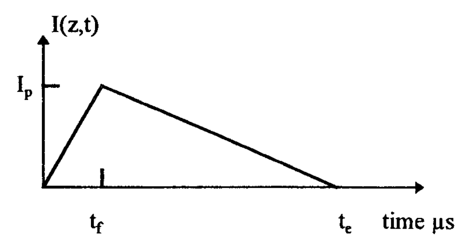

Fig. 3. A typical triangular pulse current moves from ground to cloud through upright lightning channel during lightning return stroke.

Equation (3) and (4) do not contain the total voltage which can be calculated by the following expression-

$$V^T(y,t) = V^s(y,t) + V^i(y,t) \quad (5)$$

where

$$V^i(y,t) = -\int_0^h E_z(y,z,t)dz \approx -hE_z(y,h=0,t) \quad (6)$$

here $E_z(y,z,t)$ is the incident or inducing vertical component of electric field directed positive towards the ground.

The voltages at the termination of the line is defined by the following equations:

$$V^s(y=0,t) = -I(y=0,t)r_0 - V^i(y=0,t) \quad (7)$$

$$V^s(y=l,t) = -I(y=l,t)r_l - V^i(y=l,t) \quad (8)$$

Where r_0 and r_l are the terminating resistance at left and right end, respectively, of the overhead line. Incident voltages $V^i(y=0,t)$ and $V^i(y=l,t)$ are determined from equation (6).

The equivalent circuit for the overhead telecommunication subscriber line above a perfectly conducting ground, excited by nonuniform incident vertical and horizontal electric field, follows the model given in equations (3) through (8) as is shown in figure 2.

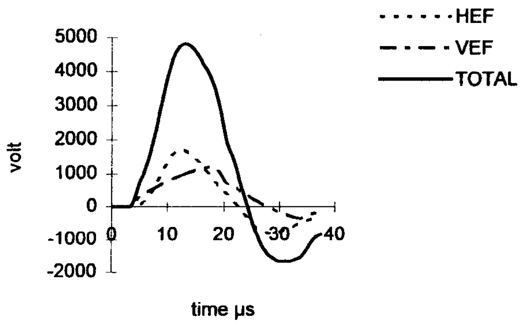

Fig. 4. Induced voltages during front return stroke at 0.5 km from the mid point of the subscriber line; dotted, and dotted-dashed line represent the unique effect of horizontal and vertical electric field respectively and the solid line the simultaneous contribution of both fields.

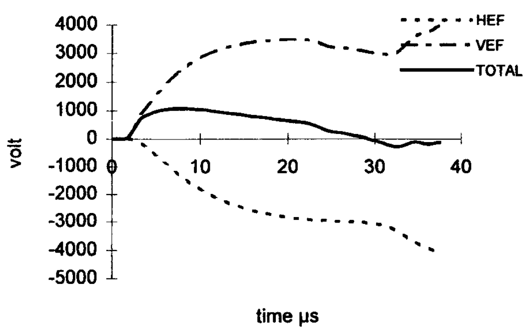

Fig. 5. Induced voltages during side return stroke at 0.5 km along the extension to the left of the subscriber line; dotted, and dotted-dashed line represent the unique effect of horizontal and vertical electric field respectively and the solid line the simultaneous contribution of both fields.

III. Results of Analysis

The numerical results presented in this paper are obtained from the finite difference solution of the coupling model expressed in equations (3) through (8). A simple triangular pulse current in fig. 3 is considered as channel current. The parameters to calculate induced voltages are as follows:

- Return stroke

$I_P = 10\ kA$, $t_f = 1.5\mu s$, and $t_e = 80\mu s$

velocity of return stroke 100 m/µs

Channel Height 4 km

- Overhead telecommunication line

length $= 1.8\ km$; height $= 5\ m$;

diameter $= 1.27\ mm$;

terminating resistance $= 600\ \Omega$

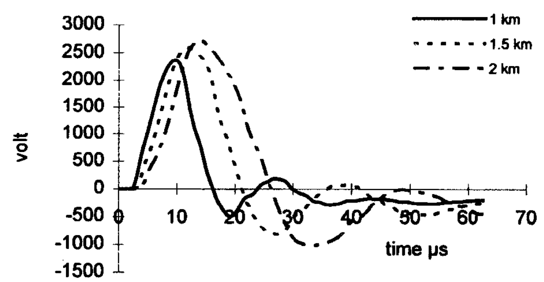

Fig. 6. Effect of line length on induced voltages at the left end during front stroke at 0.5 km from the midpoint; solid, dotted, and dotted-dashed line represent the effect of line length of 1, 1.5, and 2 km respectively.

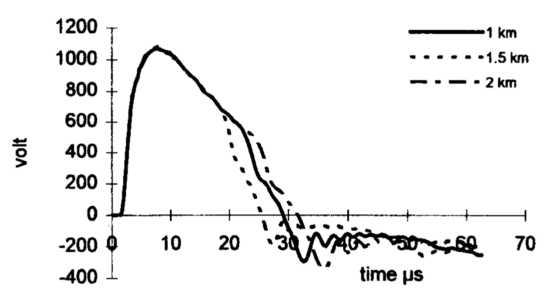

Fig. 7. Effect of line length on induced voltages at the left end during side return stroke at 0.5 km along the left extension of the subscriber line; solid, dotted, and dotted-dashed line represent the effect of line length of 1, 1.5, and 2 km respectively.

Voltage induced at the left end of the overhead telecommunication subscriber line as mentioned above due to front return stroke at 0.5 km from the mid point and side return stroke at 0.5 km from the left end of the subscriber line are shown in fig. 4 and 5, respectively. The dotted line indicates contribution of horizontal electric field when vertical electric field is set to zero, the dotted-dashed line the contribution of vertical electric field as horizontal electric field is set to zero and the solid line indicates the contribution of both fields on induced voltages. During front return stroke in fig. 4 the horizontal electric field is dominant over vertical electric field in contributing induced voltages. But during side return stroke vertical electric field contribution is dominant over horizontal electric field on induced voltages as shown in fig. 5.

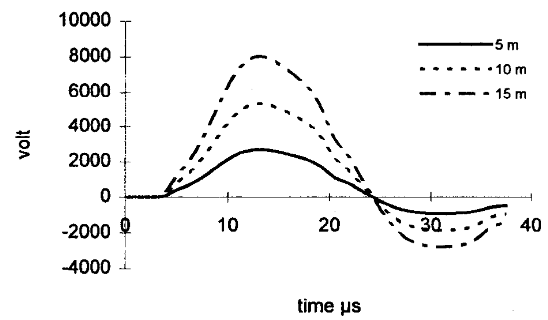

Fig. 8. Effect of line height on induced voltages at the left end during front stroke at 0.5 km from the midpoint; solid, dotted, and dotted-dashed line represent the effect of line height of 5, 10, and 15 m respectively.

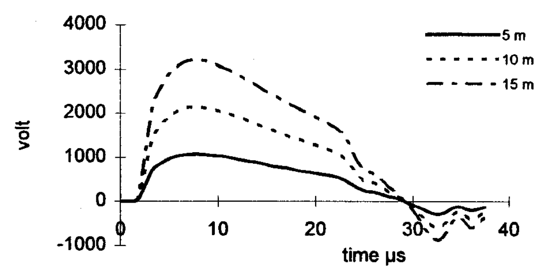

Fig. 9. Effect of line height on induced voltages at the left end during side return stroke at 0.5 km along the left extension of the subscriber line; solid, dotted, and dotted-dashed line represent the effect of line height of 5, 10, and 15 m respectively.

The effect of line length for both front and side return stroke is shown in fig. 6 and 7, respectively, where solid, dotted, and dotted-dashed line represent the effect of line length of 1, 1.5, and 2 km, respectively. For the case of front return stroke the peak induced voltages in fig. 6 increases with the line length while the steepness decreases. The line length has no significant effect on induced voltages in case of side return stroke as is shown in fig. 7.

The effect of line height on induced voltages is shown in fig. 8 and 9, respectively, for front and side return stroke. Both cases show a significant effect of line height on induced voltages. The effects produce by the front return stroke in fig. 8 is more severe in comparison with side return stroke. The severity of front return is the cause of the effect of horizontal electric field which is strong function of line height above the ground and its effect produces induced voltage of same polarity as is produced by the vertical electric field. On the other hand, vertical electric field, which presents dominating effect during side return stroke, remains constant with the elevation from the ground when the elevation is very small compared with lightning channel height. However the observed increment of induced voltage in fig. 9 is the effect of incident voltage which is given by equation (6).

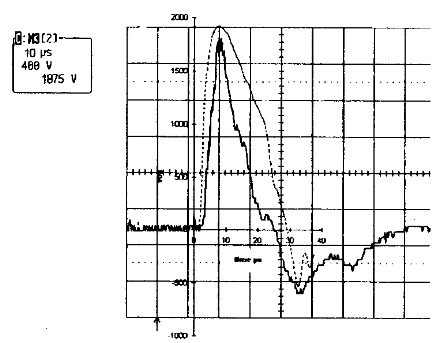

Fig. 10. Comparison between experimental side stroke data RTL00027 and numerical result as for the case of a side return stroke; solid line presents experimental data and dotted line the numerical data.

To compare numerical data with experimental data recorded by our test set-up, the co-ordinates for several lightning return strikes to the ground are collected from TNRD. One of the comparison is done between the recorded data RTL00027 and numerical data is shown in fig.10. According to TNRD detection the stroke RTL00027 is a side return stroke which occurs at 1.5 km along the line extension to the left and the channel peak current supplied is 18 kA. In our simulation we have used channel peak current of 18 kA and strike distance of 0.5 km along the extension of the line to the left while the other parameters are held the same as mentioned earlier in this section. The peak value of induced voltage obtained from our numerical results is 1925 volts whereas the recorded data gives 1875 volts. The comparison shows a good agreement between experimental and numerical data. It is to be noted that, there is a difference between the strike locations for experimental data and numerical data. However the difference is within an acceptable limit because the data supplied by TNRD has an error of ±2 km in detecting the actual lightning strike to the ground. The errors occur in lightning detection because our experimental set-up is very far from lightning detection unit.

IV. Conclusion

Both the vertical and horizontal component of electric fields radiated from a return stroke channel contribute significant effect to induced voltages on overhead lines. The consideration of front and side return stroke are important to the study of lightning induced voltages on overhead telecommunication subscriber lines as well as power distribution lines. The change of line length presents a significant effect on induced voltages during front return stroke whereas the side return stroke does not. The analysis in this paper is not only valid for telecommunication subscriber lines but also valid for overhead power distribution lines. The agreement between recorded and numerical data indicates that the numerical results are acceptable.

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